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SIX-HOUR NO-DECOMPRESSION DIVING WITH 40% OXYGEN / 60% HELIUM

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TECHNICAL REVIEW AND APPROVAL

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The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animals Resources, National Research Council.

This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

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13. ABSTRACT *(Maximum 200 words)*

U.S. Navy Special Warfare divers frequently perform long-duration, multilevel dives while breathing air, 100% oxygen, or nitrogen-oxygen mixtures in varying combinations. Dive depths range from 0-100 feet seawater (fsw) and dive durations may extend up to 6 h or more. Present decompression procedures mandate lengthy decompressions that in many cases impede mission accomplishment. This study explored the potential use of a hyperoxic helium-oxygen breathing mixture to reduce or eliminate in-water decompression time on these profiles. The protocol simulated operational diving conditions with respect to water temperature and exercise level. A total of 67 "no-decompression" dives were completed successfully using 40% O_2/60% He as the breathing mixture: 55 dives were 6 h in duration at depths ranging from 50 to 60 fsw, 6 dives were 8 h in duration at a depth of 60 fsw and 6 dives were 6.5 h in duration on a multi-level profile with depths ranging from 0-100 fsw. All dives used standard USN descent and ascent rates without decompression stops. One case of possible neurological (Type II) decompression sickness occurred during the series.

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The experiments reported employing human subjects have been reviewed and approved by the Naval Medical Research Institute's Committee for the Protection of Human Subjects.

INTRODUCTION

U.S. Navy Special Warfare (SPECWAR) divers frequently perform long-duration, multilevel dives while breathing air, 100% oxygen, or nitrogen-oxygen mixtures in varying combinations. Dive depths range between 0 and 100 feet of seawater (fsw) and dive durations may extend up to 6 hours or more. Decompression using standard, single-level decompression tables is impractical due to the multiple gas shifts involved and the severe decompression penalty imposed by the single depth assumption.

Since 1972, a number of specialized procedures have been developed to reduce the decompression requirement for these multilevel dives (1-6). These procedures capitalize on the fact that most of the dive is conducted in shallow water where inert gas uptake is either minimized or inert gas elimination occurs following a previous depth excursion. Two procedures are currently authorized for use, the Combat Swimmer Multi-level Dive (CSMD) Procedure (1,2) and the U.S. Navy Real Time Dive Planner (4-5). A third procedure, the Dry Deck Shelter Decompression Procedure Using Oxygen (6), is used to accelerate decompression once the divers have been recovered into a dry environment.

Despite the accounting for shallow dive segments, the N_2-O_2 multi-level algorithms often prescribe lengthy decompressions. Figure 1 shows a typical CSMD profile. Upon completion of this 5-hour profile, 56 min of decompression on air at 10 fsw is required. The Real Time Dive Planner prescribes an even longer time, 200 min. With the Dry Deck Shelter Procedure Using Oxygen, this time would be reduced to 45 min. Despite the long decompressions involved, these profiles have also not proven completely safe. When tested experimentally, the profile in Figure 1 using the 56-minute decompression prescribed by the CSMD resulted in 3 cases of DCS in 30 man-dives (7), an incidence of 10%. Even with 200 min of decompression, the Real Time Dive Planner predicts an incidence rate of 5%.

In a combat situation, it may not be possible to complete all the required decompression, particularly if decompression is required midway through the profile. The need for in-water decompression can also increase other dive-related risks such as hypothermia and dehydration. Moreover, adequate recompression facilities may be unavailable or inaccessible, compounding the decompression risk. A multilevel diving procedure that would eliminate the need for decompression without constricting the depth-time envelope or compromising mission flexibility would be ideal.

Two aspects of the diver's breathing gas mixture can be readily manipulated to gain no-decompression time. The oxygen content can be increased to lower the inert gas content and the inert gas diluent itself can be changed to a gas with more favorable decompression characteristics. Studies in both animals and man indicate that substitution of helium for nitrogen as the inert component of the respired gas mixture will increase tolerance to decompression (8-10). The purpose of this pilot study was to determine the extent to which these two interventions combined could reduce or eliminate decompression time in a typical SPECWAR multilevel dive profile. A secondary purpose was to collect decompression data to begin the development of a "no-decompression" curve for hyperoxic He-O_2 gas mixtures.

METHODS

Experimental Design

Our goal was to determine if we could achieve a 6-hour exposure at 60 fsw with a safe, no-stop return to the surface. A 60% He-40% O_2 mixture was selected as the breathing gas. The partial pressure of O_2 in a 40% O_2 mixture is 1.13 ATA at 60 fsw, 1.6 ATA at 100 fsw, and 2.0 ATA at 132 fsw. A 40% O_2 mixture effectively eliminates the possibility of central nervous system O_2 toxicity at 60 fsw, while still providing the flexibility for limited duration

excursions to deeper depths.

Several studies have been conducted to determine the partial pressure of helium that will allow a safe no-stop return to atmospheric pressure following a prolonged exposure. Duffner and Snider compared the bends threshold on N_2 and He in 5 subjects (10). The subjects were compressed for 12 h breathing either air or a 80% He-20% O_2 mixture, then decompressed to the surface without stops. If decompression sickness (DCS) did not occur, the subjects were reexposed one week later to a depth that was 2 fsw deeper than the previous dive. Individual no-DCS, no-decompression limits ranged from 33-36 fsw on air and from 36-50 fsw on He-O_2. Duffner and Snider concluded that a depth of 37 fsw on 80% He-20% O_2 was safe for a 12-hour exposure. This depth corresponds to an inspired helium partial pressure of 56.0 fsw.

Similar results were observed in England. In a series of unpublished dives on 80% He-20% O_2, Young observed that safe ascent to the surface was possible following a 24-hour exposure at approximately 45 fsw (inspired He pressure = 62.4 fsw). On the basis of this data, Barnard (11) assumed that ascent from 10 meters of sea water (msw) would be safe following an exposure to a He- O_2 mixture with an O_2 partial pressure of 0.22 bar (inspired He pressure = 58.7 fsw) . Barnard kept 21 subjects at a storage depth of 10 msw with an O_2 partial pressure of 0.22 ∀ 0.02 bar for at least 24 h following a one-step decompression from deeper depth. They were then decompressed from 10 msw to the surface at an ascent rate of approximately 3 fsw/min. No DCS was observed.

We selected the more conservative Duffner and Snider 56.0 fsw value as the safe inspired partial pressure of He for a 6-hour exposure. With a 60% He-40% O_2 mixture, this partial pressure is reached at a depth 60.3 fsw. A 6-hour no-stop dive to 60 fsw, therefore, should be possible. For safety, we began the study at an initial depth of 53 fsw, which is approximately 15% shallower than the calculations suggested. For subsequent titration to 60

fsw, we employed sequential design rules to select the depth based on the outcome of the previous exposures.

Subjects

A total of 41 active duty male U.S. Navy divers volunteered for the series (10 second class divers, 7 first class divers, 21 saturation divers, 2 diving officers, and 1 diving medical officer). Because of special concerns for maternal and fetal susceptibilities to decompression injury, female volunteers were not used. The physical attributes of the subjects are given in Appendix 2. The subjects were briefed individually and in groups regarding the purpose and design of the study before informed consent was obtained. New consent was given by each subject for each change in dive profile. Each subject was limited to one exposure on each profile to maximize population exposure.

All subjects underwent a comprehensive medical screening that included an experimental diving physical, detailed neurological examination, electronystagmogram, psychomotor testing, spinal somatosensory evoked responses, pulmonary function testing with flow-volume loops, and HIV screening. Subjects with chronic or acute medical conditions that might have confused the diagnosis of DCS were not allowed to dive. However, no blanket disqualifications were used in order to more closely resemble the total Navy diving population. Subjects were briefly reexamined by the Diving Watch Medical Officer (DWMO) prior to each day's dive and immediately afterwards. In addition, the DWMO saw each subject 2 h and approximately 24 h after each dive.

The following restrictions were placed on the divers:

1. No hyperbaric exposures for 1 week prior to the dive to avoid acclimatization effects.

2. No physical exercise the day of the dive. If subjects were fatigued, they did not

dive.

3. No alcohol consumption for the 24-hour periods before and after each exposure.

4. No caffeine or nicotine consumption for 12 h before each dive.

Facilities and Equipment

The dives were conducted in the "wet pot" of the NMRI Man-Rated Chamber Complex (MRCC). Two subjects were studied on each dive. The experiment simulated operational diving conditions with respect to cold and exercise level. In addition, gas composition, depth, exposure time, and compression and decompression rates were all carefully controlled.

The water temperature was initially set at 21 ± 0.5 °C. This temperature did not adequately stress the first dive pair thermally (no loss of rectal temperature) so the wetpot was subsequently lowered to 19 °C. By the third set of divers, the water temperature was set at 17 °C ∀ 0.5 °C and maintained at that temperature throughout the series. Subjects breathed 40% oxygen 60% helium via a Kirby Morgan Superlite 17B helmet equipped with a Helinaut II Ultraflow 500 exhaust system for expired gas collection. Diving dress consisted of a 1/4" neoprene wet suit with an 1/8 " neoprene undergarment. Subjects wore 5-finger, 1/8" neoprene gloves with 1/8" neoprene mitts over the gloves, along with 1/4" wet suit booties. One subject in each pair wore heat flux sensors and EKG electrodes. Both divers were instrumented with rectal thermistor (YSI Model 401) inserted 10 cm beyond the anal verge.

While at depth, subjects sat in a seat with legs extended and feet inserted into the toe clips of a locally adapted underwater cycle ergometer. This position was equivalent to approximately 120-130 degrees of hip flexion. A quick release harness was used to keep the diver in position on the seat. The subjects cycled at 60 revolutions per minute at an applied workload of 50 watts for 10 min followed by a 5-minute rest period. The work-rest cycle was

repeated throughout the exposure. The 50-watt workload was estimated to produce an O_2 consumption of 1.5 l/min STPD based on previous experience with this ergometer at NMRI.

The breathing gas mixture was prepared from pure bulk helium and oxygen components. Mixtures were made in large batches and analyzed for oxygen content with paramagnetic analysis and mass spectrometry. The gas mixture was considered acceptable if the oxygen concentration fell within ± 0.2% of the 40% target value. In addition, gas composition was continuously monitored before and during each dive with paramagnetic and electrochemical oxygen analyzers. The breathing gas was cooled to water temperature by in-water heat exchangers and then humidified by a locally designed bubble aerator.

Experimental Procedure

After pre-immersion checkouts, subjects donned their helmets and began breathing the gas mixture. Following final checks in the dry, they descended into the wetpot and remained at the surface of the water while completing in-water checks. For consistency, the time on the gas mixture prior to commencement of pressurization was kept constant at 5 min. If problems arose that required helmet removal, both subjects removed their helmets and the dive was aborted. Once the problem was resolved, the subjects re-donned their helmets and the dive time recommenced from time zero.

The chamber was pressurized to depth at 65 fsw/min. If a diver experienced problems with clearing during descent, the Diving Watch Supervisor had the authority to slow or stop the descent briefly to rectify the problem. A dive was aborted if a subject required three holds on descent. At that point, two new subjects were used and a new dive begun. This occurred twice during the series. The actual descent times for each dive are included in the chronological record of dives (Appendix 1).

Upon reaching target depth, the subjects situated themselves in the seats and prepared to

use the cycle ergometer. Depth was determined by adding the height of the water column above the shorter subjects' chest at the nipple line to the air pressure in the chamber above the wet pot (D chamber). Dive partners were paired by height prior to commencement of the series. A high-precision differential digital pressure gauge (Mensor Corp., San Marcos, TX; Serial # 3166; with overall accuracy specification of 0.04%) was used to measure depth, which was controlled via manually operated supply and exhaust valves. When depth exceeded 80 fsw, a second high-precision differential digital pressure gauge (Mensor Corp., Serial #2237) was used to measure depth. Depth gauge output was monitored throughout the dive on a Gould chart recorder. Depth was tightly controlled. Depth variations greater ∀0.25 fsw for more than 30 s did not occur during the entire series. This standard was not applied to depth control during the first 2 min after reaching depth.

Fifteen minutes after commencing pressurization, submaximal bike exercise began. The exercise continued throughout the dive for periods of 10 min followed by 5 min of rest. At the end of the designated bottom time, the subjects were brought to the surface at a target rate of 60 fsw/min. Actual rates were within 2.6 ± 2.3 % of this target with a range of 0.3% to 8.5%, except for the very shallow depths. Travel from a depth of 4.7 ± 0.8 fsw (with a range of 2.9 - 6.2 fsw) to the surface took an average time of 12.5 ± 0.7 s (with a range of 9.4 - 15.6 s). Actual individual dive ascent rates are presented in Appendix 1. The divers had their helmets removed within 2 minutes of surfacing and breathed room air from then on.

After leaving the chamber complex, the divers reported to medical for postdive evaluations, which included a neurological examination. Subjects were reexamined 2 h postdive and again the next day. For consistency, each exam was completed by the same diving medical officer.

RESULTS

A total of 67 dives were completed in accordance with all specifications. A compilation of dives completed is presented in Table 1 and a chronological record of all successful dives is given in Appendix 1.

Because of the inherent uncertainties in the approach for calculating no decompression limits and the controversy surrounding oxygen's role in decompression (12-18), a more conservative depth of 53 fsw was initially attempted. Bottom time was set at 6 h. One probable case of DCS was observed in 7 man-dives. Based on this case, the depth was lowered to 50 fsw and the series restarted. Nine 6-hour man-dives were completed uneventfully at 50 fsw. The depth was then raised to 55 fsw. Ten 6-hour man-dives were completed uneventfully at 55 fsw. The depth was then raised to 60 fsw. Twenty-eight 6-hour man-dives were completed uneventfully at 60 fsw. The dive duration was then increased to 8 h. Six 8-hour man-dives were completed uneventfully at 60 fsw.

After safely completing the 60-fsw dives, the realistic operational question of unlimited depth flexibility within this "no-decompression" envelope was briefly examined. In addition, the problem of short-duration depth excursions to 100 fsw was considered. Figure 2 illustrates the composite variable depth profile tested. This profile had an overall bottom time of 6 h 30 min and contained two 10-minute depth excursions to 100 fsw as well as a 15-minute period on the surface after the second excursion to 100 fsw to compound the decompression stress. All ascents were conducted at a rate of 60 fsw/min. Descent rates were generally 65 fsw/min or at a rate that was comfortable to the diver. Six exposures were completed without evidence of DCS. Only 6 exposures could be completed on this profile due to facility time constraints.

Symptoms

Two subjects reported significant symptoms following their dive. These cases are presented below:

<u>Case 1</u>. *Date: 30 September 1986 Subject Age: 30 years*

The diver completed the 53 fsw/6 h dive uneventfully. Four hours after the dive, the diver remained asymptomatic and went to bed. He awoke 2 h later (6-h post-dive) noting "tingling" (paresthesias) in his left hand and lower forearm, which did not resolve over 30 min. Physical examination revealed an area of patchy dysesthesia over left lower forearm and hand. The palmar surface of hand was more involved than the dorsal surface. A USN Treatment Table 6 with one extension at 60 ft and one extension at 30 ft was completed. Symptoms were slow to resolve and complete relief was not obtained until arrival at 30 fsw. Subsequent neurological assessment post-treatment was normal, including measurement of nerve conduction velocities. Past medical history was significant for two previous episodes of DCS; one in the same distribution and one presenting as left shoulder pain. Diagnosis: Probable neurological (Type II) DCS.

After this case, the depth of exposure was decreased to 50 fsw, then subsequently raised to 55 fsw and 60 fsw after multiple uneventful exposures. In retrospect, this individual may have had a "predisposition" to DCS as evidenced by 3 episodes of similar nature after provocative dives.

<u>Case 2</u>. *Date: 23 October 86. Subject Age: 34 years.*

The diver completed the 60 fsw/6 h dive uneventfully. One hour after surfacing, the diver noted sharp discrete pain in the right knee. The pain was mechanical in nature and could only be reproduced by placing the knee in one specific position. On physical examination, the pain was reproduced only at 30 degrees of flexion. In addition, the diver

had mild crepitus in both knees. The diagnosis was considered to be mechanical irritation secondary to the 6 h bike ride.

On 5 November 1986, the diver reported periods of "funny sensations" in both knees, starting 3 days postdive. Sensations increased over the day and resolved at night. The diver noted that he was involved in heavy knee exertion at home. The physical examination was completely normal except for the mild bilateral crepitus noted above. The diagnosis was again considered to be mechanical irritation.

On 14 November 1986, the diver stated that he felt he had DCS from the 6 h dive. He noted that he had dived in the chamber twice as a tender since initial episode without relief of symptoms. Treatment Table 6 without extensions was completed without relief. A bone scan completed 9 December 1986 was normal. The final diagnosis was considered to be acute and chronic degenerative joint changes. Two months postdive the diver reported that he was asymptomatic.

An additional 6 exposures were aborted during the dive for medical reasons. Two exposures were aborted (on Day 2 at 5 h 2 min into dive; on Day 3 at 4 h 11 min into dive) after debilitating substernal burning chest pain. Physical examination of both divers immediately after the dive was negative and symptoms resolved gradually over the next 2 h. It was believed that both subjects had symptoms secondary to breathing dry gas over long periods. After the second abort, a locally built in-line bubble humidifier was installed and no further pulmonary problems were encountered. Coupled with the short length of exposure, a diagnosis of pulmonary O_2 toxicity was virtually ruled out. The same two subjects were reexposed later in the series without difficulty.

An additional exposure was aborted due to an occipital paravertebral headache of gradual onset that was unrelieved by venting. This subject aborted at 2 h 9 min into the dive.

Investigation revealed that an improper diver helmet adjustment caused excessive strain on the neck muscles. The fourth abort occurred 60 min into the dive because of hemorrhoidial irritation secondary to the rectal thermistor. The fifth exposure was stopped at 1 h 28 min because of nausea that was unrelieved by venting. The diagnosis was considered to be viral gastroenteritis. The sixth abort occurred at 5 h 19 min into the dive also due to nausea and was followed by vomiting. The patient noted that he felt much better after expelling a "voluminous" amount of gas. The diagnosis was gas swallowing with gastric distention.

DISCUSSION

This pilot study was intended to examine the feasibility of long-duration diving without in-water decompression using a hyperoxic helium-oxygen mixture. Water temperature, exercise level, and dive equipment used were consciously chosen to simulate operational conditions and to provide the standard testing milieu under which most human DCS data has been obtained. The results appear extremely promising. Despite the isolated case of probable DCS at 53 fsw, 6- hour no-decompression diving appears possible at depths up to 60 fsw. Eight-hour exposures at 60 fsw and multi-level dive profiles with brief depth excursions up to 100 fsw also appear possible, but our testing of these scenarios was extremely limited.

We had two concerns in using the 12-hour data of Duffner and Snider and 24-hour data of Barnard to determine what the no-decompression depth limit for a 6 hour exposure to 60% He 40% O_2 might be. The first concern was that the body would contain more residual N_2 at 6 h than at 12 or 24 h and that this N_2 would play a role in setting the no-decompression limit. The second concern was that the elevated O_2 partial pressure in the 40% O_2 mixture might add to the risk of decompression sickness. Duffner and Snider used 20% oxygen in their study, while Barnard controlled the oxygen partial pressure at an even lower value, 0.22 bar.

Figure 3 illustrates our concern about residual N_2. The sum of the N_2 and He partial pressures in a hypothetical body compartment is plotted as a function of the exposure time during a dive to 37 fsw on 80% He 20% O_2. The compartment is assumed to exchange gas exponentially and to have a half-times for He and N_2 of 120 and 340 min, respectively. This is in accord with animal and human studies that suggest that N_2 exchange in the slower body compartments is approximately 2.7 times slower than He exchange (8,19). The slow washout of N_2 relative to the fast washin of He causes the sum of the He and N_2 partial pressures in the compartment to go through a broad maximum before declining to a final value equal to the inspired He partial pressure. At 6 h, the summed tensions are 60.97 fsw, 4.97 fsw above the inspired He partial pressure. Twenty percent of the inert gas in the compartment is N_2. At 12 h, the summed tensions are 60.61 fsw, not significantly different from the 6-hour value and still 4.61 fsw above the inspired level. However, N_2 now only comprises 9.1% of the inert gas in the compartment. At 24 h, the summed tensions are nearly equal to the inspired level and the amount of remaining N_2 is minimal. For this theoretical compartment, the risk of no-stop decompression to the surface would be greater at 6 h than at 12 h and greater at 12 h than at 24 h.

The second concern was that the elevated oxygen partial pressure might add to the risk of DCS. A possible role for O_2 in the production of DCS was first pointed out by Donald (12) and later by Eaton and Hempleman (13). Excess O_2 in tissue may act as an inert gas increasing the risk of bubble formation. Oxygen may also slow the rate of inert gas washout from tissue because of its effects on tissue blood flow. Incorporation of these two effects into probabilistic decompression models has improved their ability to fit oxygen decompression data (14,15). Nevertheless, the extent to which hyperbaric O_2 increases the risk of DCS remains unknown. In rapidly decompressed rats, Lillo found that O_2 was 40-80% as risky as

N_2 (16). In a large study of no-stop diving in humans, on the other hand, Weathersby et al. (17,18) observed that O_2, if anything appeared to have a slight protective effect. Weathersby concluded that the true magnitude of the O_2 effect, if there was one, could not exceed 40%.

Because of the uncertainties about residual N_2 effects and possible contributions of O_2 to decompression risk, we began this study at a depth of 53 fsw rather than the 60-fsw depth suggested by the data of Duffner and Snider (10). The one case of DCS observed seemed to validate this judgement. However, no further cases were observed and eventually 28 man-dives were successfully completed at the target depth of 60 fsw. If the high O_2 levels in this study did add to decompression risk, the effect was probably small. The O_2 partial pressure of 60% He-40% O_2 at 60 fsw (1.13 ATA) is 2.6 times greater than the O_2 partial pressure of 80% He-20% O_2 at 37 fsw (0.42 ATA), while the He partial pressures in the two conditions are essentially identical. If oxygen were a major contributor to decompression risk, DCS would have been expected at 60 fsw.

It is possible that depths deeper than 60 fsw and durations longer than 6 h can be achieved. The data of Barnard suggest that a depth of at least 65 fsw could be achieved on a 60% He-40% O_2 mixture. In Barnard's study, however, subjects were exposed to He at a deeper depth before beginning the 24-hour period at 10 msw. This period would have allowed for greater N_2 washout than would be achieved in a 24-hour exposure starting from sea level. This may explain why Barnard observed a somewhat higher threshold for DCS than Duffner and Snider.

Further elevation of the O_2 concentration could also be used to achieve greater depth, albeit at an increased risk of CNS and pulmonary O_2 toxicity. Table 2 shows the depths that could theoretically be achieved by raising the O_2 partial pressure above 1.13 ATA. These calculations assume a constant inspired He partial pressure of 56 fsw and no contribution of

O_2 to decompression risk.

CONCLUSIONS

Long-duration, multi-level, no-stop diving appears feasible with the use of hyperoxic He-O_2 mixtures. The low incidence of DCS we observed in this study on profiles that could not be performed on N_2 without substantial decompression was rewarding. However, the results also imply that the no-decompression envelope on He may be broader then previously thought. More work is needed to define the limits.

Our study limited the level of sustained O_2 exposure to 1.13 ATA. As noted above, if oxygen levels are increased, depths could theoretically be extended significantly. This increase in depth capability, however, must be carefully weighed against the increased risk of CNS and pulmonary O_2 toxicity. It is also possible that O_2 at partial pressures higher than 1.13 ATA will introduce decompression effects that will negate some of the benefits of oxygen.

In summary, we have shown that the use of hyperoxic He-O_2 mixtures can eliminate the decompression requirement on profiles of interest to Naval Special Warfare divers. Elimination of decompression would greatly enhance efficiency and safety of these operations. No-decompression dives exceeding 8 h at 60 fsw are theoretically possible. However, the problems of gas supply duration, hypothermia, dehydration, human sustained performance, and oxygen toxicity must be overcome before these longer dives can become a practical reality.

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TABLE 1. COMPILATION OF DIVES

Depth (FSW)	*Bottom Time (min)*	*Outcome*		
		Safe	*Possible*	*DCS*
50	360	9	0	0
50	309	1	0	0
53	360	6	1	0
53	302	1	0	0
55	360	10	0	0
60	360	28	0	0
60	480	6	0	0
Variable	390	6	0	0

TABLE 2. THEORETICAL DEPTH ATTAINABLE BY ELEVATING OXYGEN PARTIAL PRESSURE

Partial Pressure O_2 At Depth (ATA)	*Depth (fsw)*
1.1	60.3
1.3	65.9
1.4	69.2
1.5	72.5
1.6	75.8
1.7	79.1
1.8	82.4
1.9	85.7
2.0	89.0

APPENDIX 1
CHRONOLOGICAL RECORD OF EXPOSURES

Date	*Depth (FSWg)/ Bottom Time (h)*	*Descent Time (min)*	*Total Ascent Time (sec)*	*Subject Number and Incident Number or Abort (letter)*	
23SEP86	53/6.0	1	62.4	9	29
24SEP86	53/6.0	3	61.0	39	24(a)
25SEP86	53/6.0	2	Aborts	40(c)	6(b)
26SEP86	53/6.0	1	60.7	28	38
30SEP86	53/6.0	1	68.0	30(1)	31
02OCT86	50/6.0	1	58.0	27	8
03OCT86	50/6.0	1	62.3	41	22
06OCT86	50/6.0	3	57.9	20	12
07OCT86	50/6.0	3	57.7	25	15
08OCT86	50/6.0	1	*	17(d)	2
09OCT86	55/6.0	2	55.0	16	19
10OCT86	55/6.0	3	63.4	18	11
14OCT86	55/6.0	1	68.0	14	4
15OCT86	55/6.0	2	63.5	35	23
16OCT86	55/6.0	2	64.6	32	13
17OCT86	60/6.0	2	69.8	36	34
20OCT86	60/6.0	2	66.5	7	37
21OCT86	60/6.0	1	66.8	33	40
22OCT86	60/6.0	3	*	1	26
23OCT86	60/6.0	2	70.0	4(2)	25
24OCT86	60/6.0	2	65.1	3	20
27OCT86	60/6.0	3	67.3	28	12
28OCT86	60/6.0	2	69.4	19	39
29OCT86	60/6.0	2	65.4	24	6
30OCT86	60/6.0	3	69.3	9	38
31OCT86	60/6.0	8	71.8	22	11
03NOV86	60/6.0	2	68.7	8	13
04NOV86	60/6.0	2	70.3	32	21
06NOV86	Variable	4	N/A	25	10
07NOV96	60/6.0	3	72.3	41	16
10NOV86	Variable	4	N/A	2	22
11NOV86	6.0/8.0	2	67.1	27	20
12NOV86	6.0/8.0	1	69.4	9	36
13NOV86	6.0/8.0	3	66.9	21	34
14NOV86	Variable	6	N/A	3	13

**Chart recorder did not function properly*

APPENDIX 2 SUBJECT DATA					
Diver Number	*Age (yrs.)*	*Height (in.)*	*Weight (lb.)*	*Fat (%)*	*Dives*
1	27	66	154	13.1	1
2	25	68	158	11.8	2
3	29	75	185	20.5	2
4	31	67	176	14.6	2
5	35	73	230	20.0	0 + 1 Abort
6	25	71	197	18.2	1 + 1 Abort
7	44	74	202	23.7	1
8	39	70	168	19.6	2
9	21	73	208	20.2	3
10	27	75	188	15.3	1
11	29	70	169	18.2	2
12	29	66	165	20.1	2
13	25	73	179	13.9	3
14	24	66	127	10.0	1
15	29	71	188		1
16	30	71	206	20.6	2
17	32	70	140	5.8	1
18	34	71	161	14.7	1
19	26	72	176	8.3	2
20	28	69	160	15.7	3
21	24	72	156	9.9	2
22	25	71	202	16.5	3
23	27	67	171	16.2	1
24	36	67	171	11.0	1
25	30	68	161	21.5	3
26	28	67	157	17.8	1
27	25	73	178	8.1	2
28	27	73	175	18.6	2
29	26	73	210	19.0	1
30	27	69	188		1
31	33	68	162	15.9	1
32	21	70	172	15.5	2
33	31	72	212	7.1	1
34	24	68	132	15.0	2
35	22	70	160	15.7	1
36	31	71	180	12.9	2
37	31	73	153	12.5	1
38	29	72	182	16.0	2
39	25	70	179	16.7	2
40	29	74	197	20.9	1 + 1 Abort
41	33	72	180	20.3	2

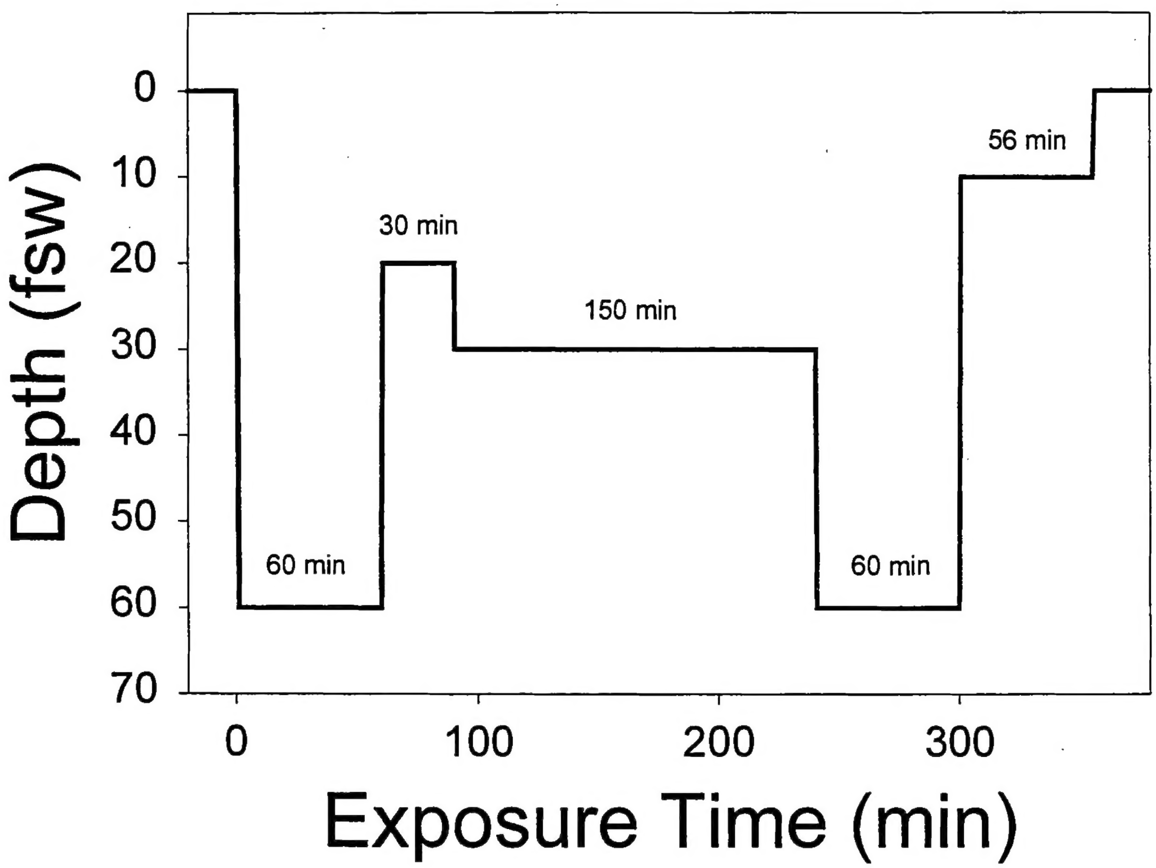

Figure 1. Typical Combat Swimmer Multi-Level Dive Profile. This 300 min air dive is composed of four segments: 60 fsw for 60 min, 20 fsw for 30 min, 30 fsw for 150 min, and 60 fsw for 60 min. Upon completion of the last segment, 56 min of decompression on air at 10 fsw is required (1,2). When tested experimentally, this profile (Profile Cb1b, ref 7) produced 3 cases of DCS in 30 man-dives. Four marginal cases also occurred.

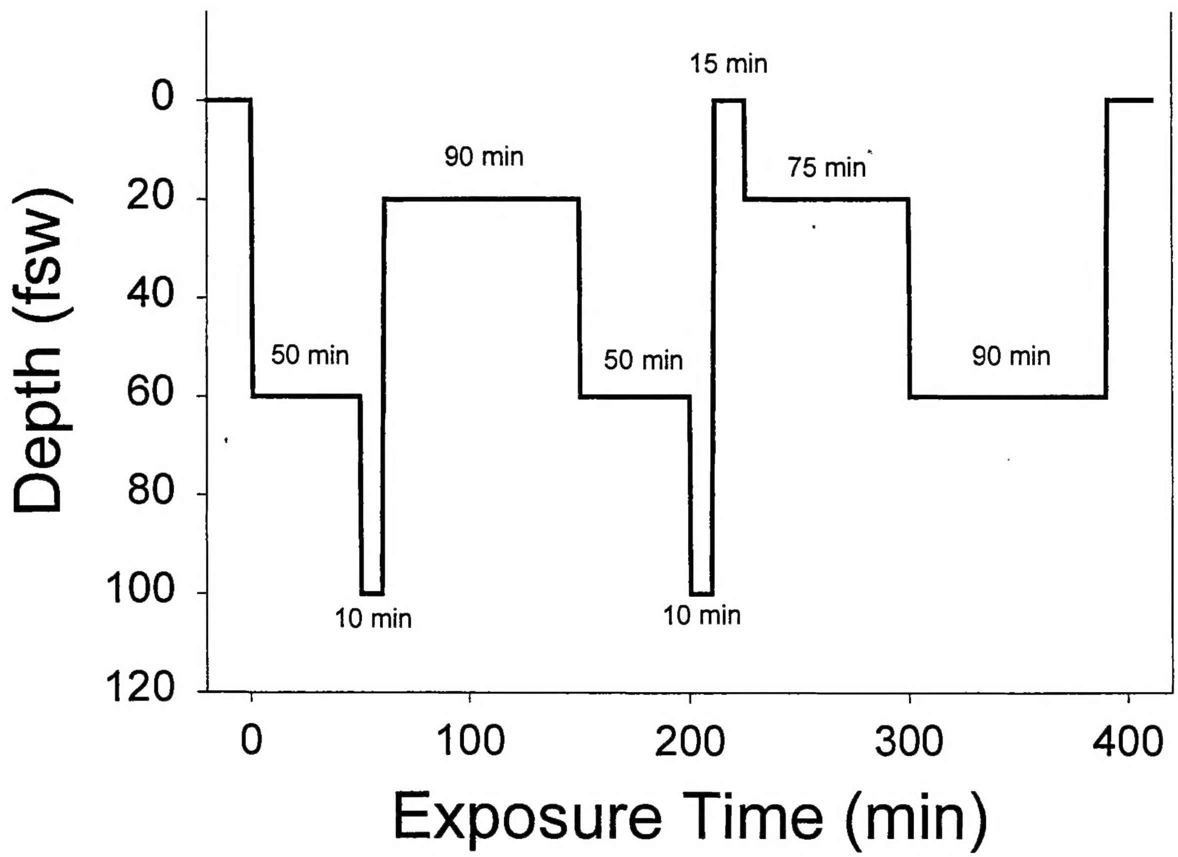

Figure 2. Variable Depth Test Profile. This 6 h 30 min profile consisted of 8 segments: 60 fsw for 50 min, 100 fsw for 10 min, 20 fsw for 90 min, 60 fsw for 50 min, 100 fsw for 10 min, 0 fsw for 15 min, 20 fsw for 75 min, and 60 fsw for 90 min. The gas mixture was 60% helium-40% oxygen throughout. Upon completion of the last segment, the divers surfaced without stops. No cases of DCS were seen in 6 man-dives.

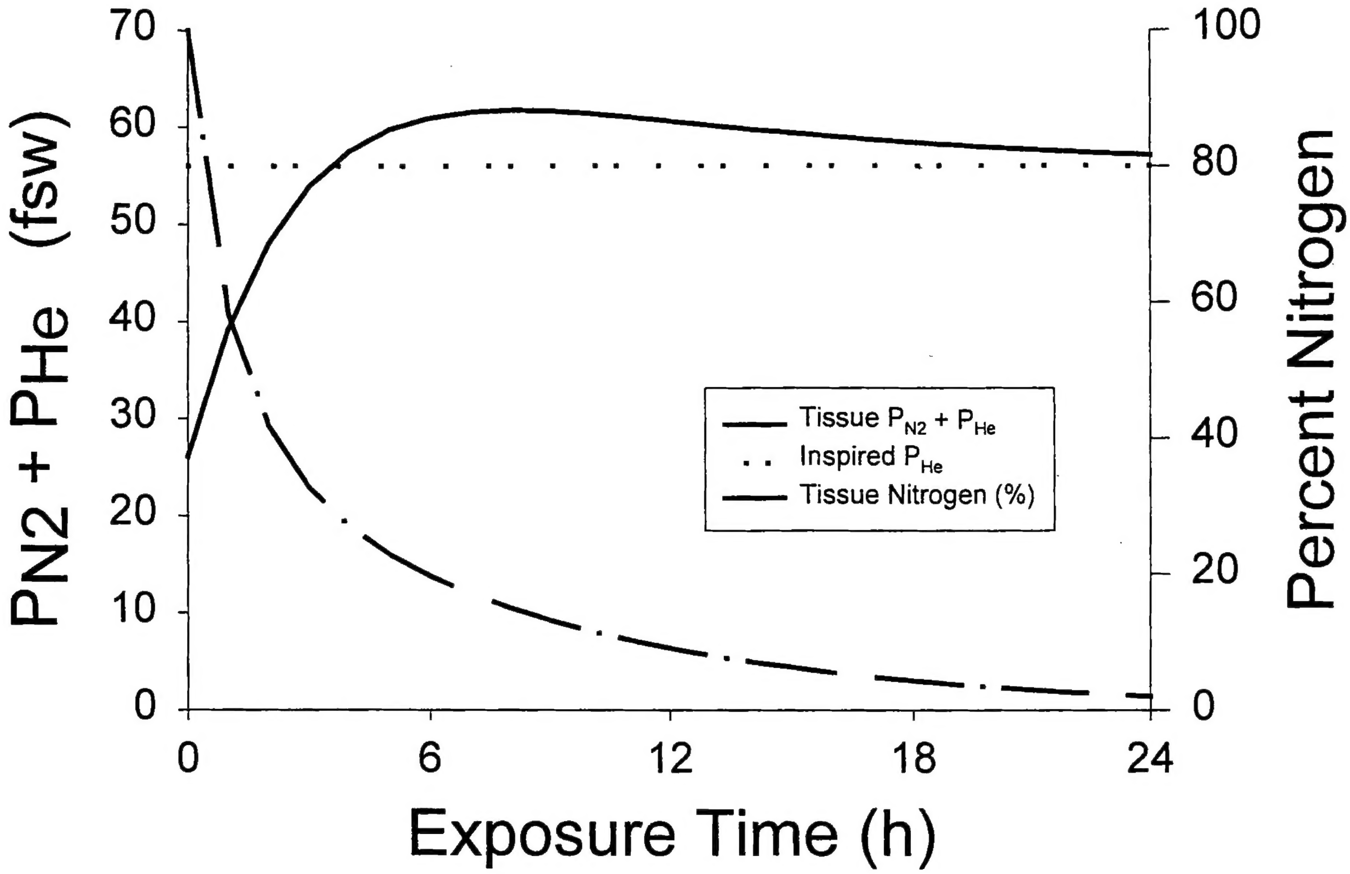

Figure 3. Gas Exchange during a 37 fsw Dive on 80% helium-20% oxygen. Dotted line shows the inspired partial pressure of helium. Solid line shows the sum of the nitrogen and helium partial pressures in a hypothetical body compartment having half-times for helium and nitrogen of 120 and 340 min, respectively. The sum of the partial pressures rises to a broad maximum between 6 and 12 hours of exposure, then declines to approach the inspired helium partial pressure. At the peak of the curve, the summed partial pressures are approximately 5 fsw higher than the inspired helium partial pressure. The fraction of tissue inert tension attributable to nitrogen (dash-dot line, right axis) declines exponentially from 100% at the start of the dive to near zero after 24 h at depth. For this compartment, the risk of DCS is higher at 6 h than at 12 or 24 h.